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Chemical Evolution of a High-Level Magma System: The Black Mountain Volcanic Center, Southern Nevada

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September 1983

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Chemical Evolution of a High-Level Magma System: the Black Mountain Volcanic Center, Southern Nevada

Abstract

A comprehensive study of stratigraphically controlled samples of both lavas and ash-flow tuffs from the Black Mountain volcanic center enables us to evaluate magmatic processes. The results of this study can be used to: 1) determine how this high-level magma system developed, 2) compare this system with other similar systems, and 3) correlate ash-flow sheets using their chemical characteristics.

The early history of the Black Mountain volcanic system was characterized by large, systematic chemical and temperature gradients in the magma chamber. The early ash flows, which sample the top of the chamber, contain chemical variations that are not consistent with crystal-liquid fractionation (e.g., depletion of light rare earth elements and enrichment of heavy rare earth elements). These ash flows preserve evidence of high thermal gradients, based on the ilmenite-magnetite geothermometer. The chemical and thermal data are consistent with thermogravitational diffusion processes which produce a volatile-rich, highly fractionated liquid at the top of the magma chamber. At this early evolutionary stage, samples of the dominant volume are represented by the precaldera lavas. These lavas are consistent with crystal-liquid fractionation processes, perhaps with some magma mixing.

However, the chemical and thermal trends in the later ash flows differ markedly from the early ash flows. These trends are consistent with a continued sampling of the dominant volume of the magma chamber—a continuation of the precaldera lava trend. The chemical trend of all the lavas and the later ash flows forms a continuous evolutionary pattern, with the lavas generally being less evolved than the ash flows. The time period between the early, anomalous ash flows and the later, nonanomalous ash flows may have been too short for a volatile-rich, gravitationally stable liquid to develop at the top of the magma chamber. The lavas, throughout the evolution of the Black Mountain system, sample various portions of the magma chamber. In contrast, the ash flows sample only the top part of the chamber. In the early stages of development, this top was anomalous; in the later stages, this top contained the same chemical trends as the dominant volume of the magma chamber.

The chemical variability of ash-flow sheets can be used for correlation purposes. As an example, significant chemical differences occur in the ash-flow sheets from the Black Mountain volcanic center compared with the Stonewall Mountain volcanic center. Using the chemical signature, we have demonstrated that the ash-flow sheets previously thought to be part of the Black Mountain center are chemically distinct and are from the Stonewall Mountain center. This type of approach can be used to evaluate lateral continuity of ash-flow units and is valuable for predicting suitability of units for nuclear containment or waste isolation purposes.

Introduction

The purpose of this study was to evaluate the evolution of a high-level silicic magma system through a study of eruptive products of the Black Mountain volcanic system. The objectives of this study were threefold:

1. To determine the variability of the eruptive units with respect to size, timing, and chemical variability both within and between eruptive units;
2. To use these variables to determine how this high-level magma system evolved; and
3. To use this system to predict the variability and evolution of other systems.

The Black Mountain volcanic system is an ideal place to study high level silicic magmas because:

1. The system had at least four major ash-flow eruptions that varied in size, timing, and composition. Therefore, these eruptions may sample different evolutionary stages of the system.
2. Lavas occur between each major ash-flow cooling unit. These lavas, in contrast with the ash flows, potentially sample deeper levels of the magma chamber.
3. The geology of the Black Mountain center is fairly well known, so stratigraphically controlled samples can be obtained.
4. The Black Mountain system is large enough to contain a great deal of variability. It is also small enough so that results can be obtained in a reasonable time framework (1 or 2 years). In contrast, the Timber Mountain Volcanic system at the Nevada Test Site (NTS) is potentially very interesting, but so large that it would be

very difficult to evaluate the complete volcanic system within 1 or 2 years.

Applications of this study fall into two major categories. The first is an understanding of the evolution of the magma(s) of Black Mountain and a comparison of this evolution with other systems. This comparison is particularly relevant to the Continental Scientific Drilling Program. One of the objectives of this program is to investigate high-level silicic systems. Several recently active systems, including Mono Craters, California; Long Valley, California; Yellowstone, Wyoming; and the Valles Caldera, New Mexico have been selected for possible future dedicated drilling. These systems span the evolutionary range from incipient precaldera stage to the final waning stage. Eruptions from Black Mountain span this temporal range in the life of a high-level system. Therefore, detailed documentation of the temporal variability of this well-exposed fossil analogue would help to focus scientific efforts at the younger systems. Thus our first goal was to determine the chemical and physical variability of the magma within the chamber as a function of time.

The second application is documentation of the spatial variability in rock properties that is recorded in the eruptive units. Understanding the nature and causes of the variability of volcanic units is essential for containment applications at NTS and nuclear waste disposal efforts at the Yucca Mountain site. What is important in this application is the ability to predict and correlate the spatial variability in rock properties.

Evolution of High-Level Silicic Magma Chambers

General Model

An important breakthrough in studying high-level magmas was the realization that ash flows result from caldera collapse and

partial evacuation of a magma chamber (Williams, 1941; Smith, 1960a). Understanding the cooling unit (Smith, 1960b) is a basic concept in the use of ash flows as a tool to study high-level silicic magmas. The

cooling unit is the fundamental genetic unit. It is an ash flow, or many ash flows, that were erupted and emplaced so fast that little or no cooling occurred between successive flows. The flows of a cooling unit therefore represent the uninterrupted, instantaneous, partial evacuation of a magma chamber. Eruptions that produce ash flows give the largest possible "instant" sample of a magmatic system (Smith, 1979).

Smith (1979) has developed a model for high-level silicic magmas (Figure 1) which relates magma volume, ash-flow eruption, timing, and composition. In this model the magma chamber consists of compositionally stratified magma with primitive, mantle derived magmas at the base. Overlying the primitive magma is a derivative magma which consists of a mixed magma lower part, a dominant volume central part, and a most fractionated upper part. Eruptive dynamics are such that draw-down of the magma during eruption of ash flows is governed by the maximum eruption level

level (see Figure 1). Large ash flows, greater than 10^2 km^3 associated with large-volume chambers, will typically sample only the most fractionated upper magma and perhaps some of the dominant volume. In contrast, smaller ash flows less than 10^2 km^3 associated with smaller volume chambers, have the opportunity to sample the entire spectrum of the chamber. In this respect, the Thirsty Canyon ash flows associated with the Black Mountain center fall into a very interesting volume range ($10^0 - 10^2 \text{ km}^3$).

Chemical Variability of Ash Flows and Lavas

The primary way to understand the processes acting within a high-level magma chamber is to study material erupted from the chamber. Ash flows and associated deposits are the most widespread and voluminous volcanic products of high-level silicic

Figure 1. Generalized Smith model showing relationship between volume, depth, periodicity of eruptions, and composition.

systems. They are important in evaluating the characteristics of the magma because they represent large, instantaneously erupted, quenched samples of the magma within the chamber. Lavas, in contrast, represent less voluminous leakage from various levels within the magma chamber and generally occur along fracture systems. Because of their limited volume, lavas are restricted in areal extent. Both ash flows and lavas are periodic samples of an evolving magma chamber. The ash flows represent a record of the magma in the upper portion of the chamber just prior to eruption. As a result they provide the largest glimpse of the magma in the upper portion of the chamber. Lavas complement this picture by providing smaller samples at additional points in time, as well as samples from different parts of the chamber. Taken together these two types of eruptions provide progress reports on processes acting within the chamber, and thereby record the evolution of a magma system.

The chemical nature of ash-flow tuffs is a result of both primary and secondary processes. Primary processes are those that occur in the magma chamber; secondary processes are those that occur during and after eruption. Secondary processes consist of:

1. Eruptive mixing,
2. Transportation,
3. Deposition,
4. Welding,
5. Crystallization of the glass
(devitrification),
6. Vapor phase alteration, and
7. Hydration of the glass.

Secondary processes can mask primary magmatic processes. Most of the effects of these secondary processes can be eliminated by using quenched glassy pumice, which represents vesiculated magma, rather than the whole rock, which includes transportation and depositional effects. By using glassy samples we can also eliminate variation due to crystallization and vapor-phase alteration.

Variability observed within a flow may reflect heterogeneities within the top of the magma chamber, or eruptions which sam-

pled different levels in the chamber. In some small systems, mixing of magma has been observed in individual pumice blocks. This can be interpreted as indicating the eruption has drawn the magma down to a depth in the chamber below the most fractionated volume to the dominant volume. However, for flows containing variable pumice populations, careful stratigraphic sampling is required to answer the question of depth of draw-down. Variability due to eruption can be evaluated by documenting the spatial variation within and between flows of known relative ages. After inferring the nature of the chemical variability of the magma chamber, it is possible to evaluate the effects of the secondary processes that lead to the total variability of the eruptive unit. It is this total variability of the physical and chemical properties of the ash-flow tuff that is important in predicting if a particular rock volume is laterally continuous and sufficiently homogeneous to be used as a medium for nuclear testing. Rock used for nuclear testing must be laterally continuous and contain uniform physical and chemical properties. Ash-flow tuffs used for waste disposal applications require these same properties.

Processes That Can Cause Variation within the Magma Chamber

Some of the major processes that operate within a magma chamber can be conveniently categorized according to the states of the system:

a) *Crystal-liquid processes.* These include any separation of liquids from crystals. The major processes are (1) partial melting of a source rock and (2) fractional crystallization of the liquid. In both (1) and (2) the chemical variation can be predicted because the partitioning of chemical elements between liquids and minerals is fairly well known. Both the partial melting and fractional crystallization processes can be modeled, and the predicted data array can be compared to the observed data for consistency.

b) *Liquid-only processes—immiscibility.* This term refers to the separation of two chemically contrasting liquids from a homogeneous liquid. As with crystal-liquid processes, the chemical partitioning of elements between coexisting liquids is reasonably well known, and the process can be evaluated by comparing predicted trends with observed trends.

c) *Liquid-only processes—magma mixing.* This is the mixing of magmas of contrasting chemical compositions to produce an intermediate composition. Magma mixing can be evaluated quite easily by multiple linear regression techniques, which use the chemical elements as the variables in the linear equations. In addition, element ratio diagrams have been used successfully in evaluating magma mixing.

d) *Liquid-vapor processes—vapor separation.* This term refers to the separation of a vapor phase from the liquid. The process is difficult to evaluate because the vapor phase is no longer present. However, there is limited data available on the partitioning of elements between silicate liquids and vapor. Furthermore, the data can be compared to the rock pattern data for consistency.

e) *Liquid processes—thermogravitational diffusion.* In many high-level silicic magma systems the highly fractionated top of the magma chamber contains compositional variation that is inconsistent with any plausible scheme involving the processes described above. Shaw et al. (1976), Hildreth (1979), and Smith (1979) have proposed a process which they call "convection-driven thermogravitational diffusion." This model has been discussed in detail by Hildreth (1979, 1981). Because it is thought to be very important to the evolution of high-level silicic magmatic systems, it will be summarized below.

The thermal input that drives the system are intrusion of basaltic magma derived from the mantle. The dominant volume of silicic magma is created primarily by melting of the lower crust. Processes superimposed on this magma volume are crystal fractionation and mixing of basaltic magma

with silicic magma, which lead to compositional variation within the dominant volume. This dominant volume will convect, driven by the continued addition of heat from basaltic magma. Gradients in temperature will occur near the interface between this magma and the surrounding rocks. Chemical gradients, especially with volatiles, will be concomitant with the temperature gradients. Hildreth (1977, 1981) visualizes a main convection cell with an ascending central part driven by heat from below. Temperature and chemical gradients are greatest near the walls, and it is here that an ascending chemical boundary layer forms a low density counterflow that rises. This counterflow concentrates diffusing chemical species and enriches the growing upper part of the magma chamber (Hildreth, 1981, p. 10173). These chemical and temperature gradients result in the formation at the top of the magma chamber of a gravitationally stable, volatile-rich magma. The liquidus temperature of the top part of the magma chamber is reduced because of the high volatile content. The result is a lowering of the phenocryst content in the magma toward the top chamber. It is in this top part of the magma chamber that great enrichments and depletions in minor elements have been inferred. According to this model, the enrichments and depletions develop because of the combined effect of thermal and volatile gradients. These gradients may control the degree of polymerization of the melt, ionic complexes, and cation site availability in the melt (Mahood, 1981). A fundamental part of this model is that most of the diffusion takes place across the boundary layer, where thermal and chemical gradients are the highest. This volatile-rich, gravitationally unstable, boundary layer convects upward and concentrates at the top of the magma chamber (Shaw, 1974; Shaw et al., 1976).

Evaluation of this "thermo-grav" model is somewhat nebulous, because some of the factors that are used to evaluate the model are ad hoc arguments used in developing the model. The "thermo-grav" process has been shown to occur in nonsilicate

liquid systems (see Hildreth, 1981, for a review). A major drawback in the model is the fact that in the chemical diffusion process the diffusion rates in silicate liquids are orders of magnitude too slow to be viable mechanisms. However, fundamental to the model is the coupling of chemical diffusion in a temperature gradient (the Soret effect) with convection of a volatile-rich boundary layer.

Thermal gradients inferred in the magma chamber from the ash-flow tuffs can be documented by use of the ilmenite-magnetite geothermometer. Both temperature and compositional gradients have been documented from ash-flow tuffs; the current state-of-the-art thinking is that if it does not fit crystal-liquid equilibrium, then it is "thermo-grav" diffusion. However, Michaels (1983) disagrees. He has shown that chemical gradients in the Bishop Tuff could be produced by large amounts of crystal separation of phenocryst phases. The major drawbacks to the crystal fractionation

process theory are (1) viscosities of the liquids are too high to allow crystal settling in any reasonable time span of the life of the magma, and (2) there are no rocks present that indicate that crystals have accumulated. In fact, in most systems studied, the phenocryst phases are in equilibrium with the glass surrounding them (i.e., they have not formed elsewhere and settled to a new level in the magma chamber).

"Thermo-grav" diffusion should be most effective in magmatic bodies that have high surface-area-to-volume ratios. Bodies that would be most effective would be slab-like chambers with a high rate of heat input to prevent crystallization and high thermal gradients with the wall rock. Recent mathematical modeling (Spera et al., 1982) has shown that coupling Soret diffusion with convection can produce sizeable chemical fractionation of magma, provided that the temperature gradients can be maintained over the life of the magma chamber.

The Black Mountain Volcanic Center: An Example of a High-Level Silicic System

General Geology

Black Mountain volcanic center is located just off the northwest side of the Nevada Test Site (NTS), north of the large Timber Mountain-Oasis Valley volcanic center. The eruption units of Black Mountain form the Thirsty Canyon Tuff (Figure 2). Early workers divided this into five ash-flow sheets (Table I).

The two oldest members of the Thirsty Canyon Tuff are the Rocket Wash and Spearhead cooling units. These are separated only by the airfall at the base of Spearhead. The record of erosion at this contact is negligible. Each cooling unit is about 100–150 km³* (Christiansen, 1979). The overlying cooling unit, the Trail Ridge member, is separated by a distinct erosion break. Lavas occur locally, near the source, between the Spearhead and Trail Ridge members. The volume of the Trail Ridge is estimated to be about 50 to 100 km³.*

The next cooling unit, the Gold Flat member, has a distribution distinctly different from that of the underlying ash-flow units. Lavas, gravels, and airfall occur between Gold Flat and underlying Trail Ridge within, and just outside, the caldera. Locally the Gold Flat was confined by fault scarps that developed in the older units. The Gold Flat member is about 20 km³ (Christiansen, 1979). The uppermost ash flow, the Labyrinth Canyon,* occurs as a

* New data (Noble et al., 1983, and in press) would decrease the volume at the Spearhead and Trail Ridge members and remove the Labyrinth Canyon member from the Thirsty Canyon Tuff. The original Spearhead member was first described from Goldfield, north of Stonewall Mountain. It is now known that this ash-flow sheet is different from the "Spearhead" of Thirsty Canyon and was most likely to have been erupted from the Stonewall Mountain volcanic center. The Spearhead member of Thirsty Canyon has been tentatively renamed the Pahute Mesa member (Noble et al., in press), because the earlier name (Spearhead) takes precedent.

Figure 2. General geology of Black Mountain and vicinity. Northwest of dashed lines the ash flows are from Stonewall Mountain. The Thirsty Canyon Tuff occurs southeast of this line.

ponded flow within the vicinity of the caldera and is only a few cubic kilometers in volume. Christiansen (1979) suggests that each successive cooling unit in the Thirsty Canyon Tuff was smaller than, and probably separated by, a progressively longer time than the preceding unit.

Black Mountain is a set of nested collapse structures and constructional volcanoes about 14 km across and formed a single source area for the ash-flow sheets. The magma underwent cyclic evolution resulting

in early eruption of lavas to build a volcanic cone followed by a major pyroclastic (ash-flow) eruption. The eruptions followed one another closely and, except for the Rocket Wash and Spearhead members, were separated by lavas of various compositions. The ash-flow eruptions produced collapse structures and the calderas that were produced are nested within earlier ones. The total life of the system was probably less than a million years.

Table I. Stratigraphy of Thirsty Canyon Tuff (after Christiansen, 1979).

Ash-flow members	Estimated size	Estimated time between ash-flows	Lavas
Labyrinth Canyon	1	—	Basalt
Gold Flat	20 km ³	10 ⁵	Hidden Cliff
Trail Ridge	50 km ³	10 ⁵	Pillar Springs Basalt
Spearhead	100–150 km ³	10 ³ –10 ⁴	Basalt Yellow Cleft Ring Trachyandesite
Rocket Wash	100–150 km ³	10 ² –10 ³	Ribbon Cliff

Sampling and Analysis of the Eruptive Products

The Black Mountain volcanic center was mapped by D. C. Noble and R. L. Christiansen of the U.S.G.S. in the early 60s. Noble, Christiansen, and O'Connor published a series of quadrangle maps and reports on the Black Mountain caldera and its eruptive products (Christiansen and Noble, 1968; Noble and Christiansen, 1968; O'Connor and others, 1966; Noble and Christiansen, 1974).

Samples of the Black Mountain products are given in Table II (see Appendix A). Sampling was designed to evaluate the primary compositional variation of the magma. In order to do this, glassy pumices were used where available. Samples were taken so that within-outcrop variation could be evaluated as well as between-outcrop variation. Both lateral and vertical variations of ash-flow members were sampled. Because glassy samples are more abundant at the bottoms and tops of cooling units, these are overemphasized in this sampling scheme. However, these samples give information as to the maximum variation of the upper part of the magma chamber.

Samples of the ash flows were also taken to evaluate variation caused by trans-

portation and deposition. Whole rock compared with pumice samples from the same outcrop can be used to evaluate these processes. Finally, samples of devitrified and glassy rocks, as well as hydrated and nonhydrated glass in the same outcrop, were taken to evaluate the effect of recrystallization and hydration.

All of the lavas were sampled to determine their chemical variation. Sampling usually involved unaltered vertical sequences; secondary alteration of lavas was usually minor.

117 samples were analyzed. 110 samples were analyzed by instrumental neutron activation analyses (INAA) at LLNL. 80 samples were sent to Barringer Magenta, Ltd. for inductively coupled plasma emission (ICP) analyses. 47 wet chemical analyses were provided by D. C. Noble.

The results of the chemical analyses are given in Tables IIIa, b, c, and d (see Appendix A). For analytical convenience, these tables are divided into IIIa—Major Elements, IIIb—Rare Earth Elements, IIIc—Other Trace Elements, INAA Data, and IIId—ICP Trace Elements. Table IV (see Appendix A) is the temperature-oxygen fugacity data determined from electron microprobe analyses of coexisting ilmenite-magnetite based on the methods of Spencer and Lindsley (1981).

Plus or minus values are based on the 95-percent confidence limits of both the microprobe analyses and the experimental data of Spencer and Lindsley (1981).

Evaluation of Secondary Processes

Two major secondary processes which affect glassy ash-flow tuffs are hydration and devitrification (recrystallization). Hydration is ubiquitous and results from the interaction of groundwater and the glass. Devitrification occurs mainly because the glass is inherently unstable, and during slow cooling (away from cooling surfaces) the glass devitrifies. Ash-flow tuffs dominantly consist of devitrified rock.

Nonhydrated glass is relatively rare and occurs under unusual circumstances where the glass has been protected from groundwater. We have evaluated one sample of nonhydrated glass surrounded by hydrated glass (Table V) by INAA techniques. No ICP analyses could be obtained because the sample size was too small.

Adjacent samples of glassy and recrystallized samples are relatively easy to obtain. Vitrophyres often have sharp contacts with the overlying devitrified welded ash-flow tuffs. Table VI shows a complete analysis of two adjacent samples. In comparing the difference between two samples, we used the standard deviation obtained from replicate analyses, and we then determined

Table V. Comparison of hydrated and nonhydrated glass.

	Hydrated glass	Nonhydrated glass	Difference at 95% C.I.
La	92.840	93.260	No
Ce	184.800	205.100	No
Sm	13.470	15.310	Yes
Eu	0.052	0.051	No
Tb	2.046	2.331	No
Yb	10.820	12.440	No
Lu	1.910	2.173	No
Sc	1.440	1.200	No
Zn	184.500	176.300	No
Rb	298.600	371.700	No
Sb	0.600	0.650	No
Cs	5.120	6.210	No
Hf	20.120	21.320	No
Ta	5.860	6.890	No
Th	39.440	44.170	No

Table VI. Comparison of glass and recrystallized ash-flow tuff.

		Glass	Recrystallized glass	Difference at 95% C.I.
SiO ₂	(in %)	69.07	68.35	No
Al ₂ O ₃	(in %)	14.78	14.94	No
Fe ₂ O ₃	(in %)	03.37	03.38	No
CaO	(in %)	0.84	0.68	No
MgO	(in %)	0.32	0.23	No
TiO ₂	(in %)	0.42	0.44	No
MnO	(in %)	0.17	0.17	No
Mg ₂ O	(in %)	05.46	06.03	Yes
H ₂ O	(in %)	05.76	05.58	No
P ₂ O ₅	(in %)	00.08	00.08	No
La	(in ppm)	160.	157.	No
Ce	(in ppm)	287.	277.	No
Sm	(in ppm)	14.	15.	No
Eu	(in ppm)	0.90	0.92	No
Tb	(in ppm)	1.4	1.3	No
Yb	(in ppm)	6.2	6.1	No
Sc	(in ppm)	9.4	10.3	No
Zn	(in ppm)	128.	132.	No
Rb	(in ppm)	123.	131.	No
Sb	(in ppm)	0.21	0.23	No
Cs	(in ppm)	1.	1.7	No
Hf	(in ppm)	20.4	20.7	No
TA	(in ppm)	2.4	2.4	No
Th	(in ppm)	16.6	16.6	No
Be	(in ppm)	3.80	3.9	No
Sr	(in ppm)	19.4	19.	No
Zr	(in ppm)	796.	847.	No

if there were element-by-element differences at the 95-percent confidence limit.

With respect to the glassy versus recrystallized welded ash-flow tuffs, the only significant difference observed (at the 95-percent confidence level) was in Na_2O (Table VI). This was expected because the glasses have excess alkalis (more than can be held in the feldspars when recrystallization occurs) and alkali loss would therefore be expected when the glass recrystallizes.

The nonhydrated versus hydrated glasses show general agreement (Table V). However, Sm and Cs show statistical differences which, by themselves, are not consistent with the other element-element comparisons. We suspect that there is an analytical error here due to the small sample size. The comparison of recrystallized versus glassy rocks has much more application because of the dominance of recrystallized (devitrified) rocks in ash flows.

Correlation of Ash-Flow Members Using Chemical Analyses

Significant differences in chemical variation occur from one ash flow to another, especially in the trace elements. Potentially this has an important application in determining whether or not a series of ash flows can be correlated based on their chemical variability. This type of study can be used to support or reject correlations based on field mapping and petrographic studies. If it serves no other purpose, it can define areas that need to be reexamined.

We have used this technique to show that what was originally mapped as the Spearhead and Trail Ridge members, north of Black Mountain in Civit Cat Canyon, is chemically distinct from the Spearhead and Trail Ridge members in Thirsty Canyon. A very conservative statistical test is an element-by-element two-sample T test. With this test, the variability of trace ele-

ments at the Civit Cat Canyon section can be compared with the Thirsty Canyon type section. This test makes clear that the Civit Cat Canyon section is chemically different from the Thirsty Canyon section. Early workers extended the Spearhead ash-flow sheet from Civit Cat Canyon to north of Goldfield—over 30 miles. If our comparison of ash-flow tuffs from Civit Cat Canyon with the Thirsty Canyon ash-flow tuffs is confirmed by field work, this would appreciably change the size of the Spearhead and the overlying Trail Ridge eruptions. Recent paleomagnetic work by Noble et al. (1983) show that the tuffs north of Stonewall Mountain, previously mapped as Spearhead and Trail Ridge, have a different thermal remnant magnetic direction from that of similar-appearing tuffs in Thirsty Canyon.

The Labyrinth Canyon ash-flow member of the Thirsty Canyon Tuffs has a chemical composition that by inspection appears to be decidedly different from the other trends of the Thirsty Canyon Tuff. In the field, there is no caldera observed in Black Mountain that can be related to these tuffs. The possibility exists, then, that the Labyrinth Canyon Tuffs are not related to the Black Mountain volcanic center. We compared the chemical variability of the Civit Cat Canyon rocks with those of the Labyrinth Canyon using this two-sample T-test method. The results of this very conservative test show that in all elements except Zn, the variability of the tuffs in Civit Cat Canyon are indistinguishable from the Labyrinth Canyon Tuffs. The thermal remnant magnetic directions are also identical (Noble et al., 1983).

This type of study demonstrates that chemical variation can be used to evaluate field correlations and can also constrain models that are based on field relationships. Combined field, petrographic, paleomagnetic, and chemical studies can be used to determine the correlations from an eruptive center.

Evaluating Magmatic Processes

Background

One of the most useful methods for inferring magmatic processes is to evaluate the distribution of incompatible trace elements. Incompatible elements are those elements that are not incorporated into the minerals during liquid-crystal equilibrium. For incompatible elements, the ratio of concentration of an element in the minerals to that in the liquid (distribution coefficient) is less than 1.0. For highly incompatible elements, the distribution coefficient is less than 0.1. Therefore, in any magmatic process in which crystals and liquids were in equilibrium and then separated, the concentration of a highly incompatible element will always increase markedly in the liquid. Processes such as fractional crystallization of the early formed crystals from the liquid, or partial melting of a source rock with separation of a liquid, can be evaluated easily by examining the distribution of these incompatible elements.

In our preliminary analyses of the data we have selected a few trace elements in which the distribution coefficients are fairly well known and these elements can be analyzed with a high degree of precision. The elements that we used for this evaluation are the rare earth elements (REE) (La, Ce, Sm, Eu, Tb, Yb, Lu) because they are all (except for Eu) incompatible elements with respect to the common magmatic silicate minerals and have decreasing incompatibility from the light REEs (La, Ce) to the heavy REEs (Yb, Lu). Furthermore, Eu is compatible (distribution coefficient greater than 1.00) with feldspars, and liquids that have been separated from plagioclase will show an Eu depletion. Other incompatible elements we have used in this preliminary analyses are Th and Hf, both of which are highly partitioned into the liquid during crystal liquid equilibrium. Any process that involves separation of solids from liquids must show a regular increase in these in-

compatible elements as the degree of fractionation increases.

Figure 3 shows a plot of two highly incompatible elements, Hf and Th. The general linear trend is consistent with either a (1) crystal-liquid fractionation process, (2) mixing of magmas, or (3) a combination of mixing or fractionation. This trend could, for example, be produced by a mixing of a silicic magma with a mafic magma.

Magmas derived by mixing of a mantle-derived liquid (mafic liquid) with a crustal-derived liquid (silicic liquid) often show the same type of enrichment trends as a fractional crystallization or a partial melting trend, with respect to element-element

Figure 3. Plot of Hf-Th for all of eruptive products (lavas and ash flows) of Black Mountain.

plots. This is because crustal rocks are enriched in incompatible elements, and liquids derived by partial melting of these rocks are highly enriched in the incompatible elements. In contrast, mantle rocks have low concentrations of incompatibles, and therefore the liquids derived from the mantle are relatively low in incompatible elements. Mixing of mantle-derived liquids with crustal-derived liquids will produce linear trends on element-element plots. These trends are similar to those produced by crystal-liquid separation. However, mixing produces hyperbolic-type trends in element-ratio plots (element-ratio a/b versus element-ratio c/d).

Hildreth (1979, 1981) has shown that certain trace elements (especially the REEs) are sensitive to processes occurring in the silicate liquid itself. (We discussed this phenomenon earlier in the section on magmatic processes.) Although the exact process is not known, the effects can be observed in selected trace elements, especially the REEs. The light REEs (e.g., La, Ce) are depleted in the low temperature liquid and enriched in the higher temperature liquid, whereas the heavy REEs are highest in low temperature liquid and are depleted in high temperature liquid. With crystal-liquid equilibrium, both the light and heavy REEs should fractionate together; that is, both are enriched in the lower temperature liquid.

Approach

In the following section, we use several types of plots particularly sensitive to the major petrologic fractionation processes. This will enable us to qualitatively compare chemical trends present in the lavas and the ash flows. We can thereby infer the major petrological processes as a function of time and depth in the chamber.

1) REE normalized plot* (Figures 4, 5A, 5B, 9, 13, 14, 15, 16, 17). In these plots

* REE plots are normalized to a chondrite meteorite to avoid the effect of variable abundances of odd- and even-numbered elements.

abundance of the various rare earth elements for individual samples representing different stratigraphic levels within a lava flow or ash-flow sheet are highlighted. As noted above a simple fractional crystallization scheme would lead to a general upward shift of the curve as the liquids become more fractionated. In the simplest case, where the base of the ash-flow sheet represents the top of the magma chamber and the most fractionated liquid, the curve representing samples from the base would lie above the curve for samples from the top (lowest samples of magma chamber) of the ash-flow sheet for all elements except Eu. As noted above, Eu is preferentially taken into the feldspar structure, so if feldspar fractionation is occurring it will also lead to an Eu depletion in the most fractionated liquids. This type of plot is particularly sensitive to distinguishing the simple crystal fractionation scheme described above from the liquid-only fractionation scheme. In that case, the inverse fractionation of heavy and light REEs noted above will lead to a "crossover" pattern on the plot. Samples lowest in light REE will be highest in the heavy REE. We refer to this as an inverse relationship in order to contrast it with the simple crystal fractionation pattern.

2) REE enrichment plot (Figures 6, 12). Enrichment factors are defined by the concentration of an element in the earliest part of the eruption divided by the concentration in the latest part of the eruption. Therefore, the absolute value of the enrichment depends on the depth of the draw-down of the eruption. They are a convenient way of portraying the sense and degree of compositional zonation in a chamber. The inverse relationship mentioned above is particularly striking on this type of plot, in that light REE would lie below the no enrichment line, whereas heavy REE would lie above.

3) REE element-element plots (La vs Yb—Figure 7). These plots represent a third way of portraying the rare earth element data. If one chooses a light and heavy REE,

then the inverse relationship is easy to identify. The advantage in using this type of plot is that it allows us to explore compositional relationships between the lavas and the ash-flow sheets.

4) Major element correlation plots (Figure 8). In this type of plot, major elements are plotted against SiO_2 content. Each oxide is plotted against SiO_2 to illustrate the variation with increased fractionation of the magma. In this report, we use these plots to make inferences about the relationship between the lava samples and the ash-flow samples.

5) Other incompatible element-element plots (Th vs Hf—Figures 10, 19). Th and Hf are both highly incompatible and therefore partitioned into the liquid during crystal liquid equilibrium. As a result, plots of these elements are a sensitive measure of the degree of fractionation. In this study, we use this type of plot to constrain the relationship between the lavas and the ash flows.

6) Other element-element correlation plots (Eu/Eu(pred) vs Th—Figures 11, 18). This type of plot allows additional monitor-

ing of the degree and type of fractionation occurring. It is used in this study to compare the type of magma evolution represented by the ash flows with the pre-ash-flow lava flows.

In summary, we use a variety of plots of incompatible elements to highlight variation in the Black Mountain volcanic center. REE normalized plots and REE enrichment plots for stratigraphically-controlled samples are used to identify elements concentrated upward in the magma, and those concentrated downward, at one instant in time. Alternative patterns can be interpreted to represent different fractionation mechanisms acting within the chamber. Element-element plots of a variety of types can be used to monitor the degree of fractionation of given liquids. These plots allow us to establish compositional relationships between precaldera lavas and ash-flow sheets. The plots also allow us to monitor the overall evolutionary pattern of the system, as represented by Figure 3. Taken together, they provide a powerful means of establishing the nature and causes of the chemical evolution of the system.

Magmatic Evolution of the Black Mountain System

For convenience, we separate the magmatic history of the Black Mountain system into three time periods. This allows us to look in more detail at the evolving magma system. We can also make comparisons between processes inferred to have been active in the early time frame and those inferred to have been active later in its history. The first period of the system is sampled by precaldera lavas and the ash flows of the Rocket Wash and Spearhead members. The second period of the system is sampled by the post-Spearhead lavas and the ash flows of the Trail Ridge member. The final waning stage of the system is the post-Trail Ridge stage, and it is sampled by the Pillar Springs lava flows, the Gold Flat ash flows of the member, and the Hidden Cliff lavas. Final interpretation of the magmatic evolu-

tion will require obtaining age dates of the eruptions and final field checking of the suspect correlations mentioned earlier. Using the generalized time scale established by Christiansen (1979) and the available samples analyzed to date, we concentrate in this report on documenting and comparing the early evolution of the system with the later evolution.

Early Evolution: Precaldera Lavas and Rocket Wash and Spearhead Ash Flows

The Rocket Wash and Spearhead members are the earliest caldera-forming eruptions. Both are compound ash-flow sheets which show little evidence of erosion

between them. These ash flows contain similar types of REE patterns. Figure 4 shows the REE pattern for the Rocket Wash member. Figures 5a, 5b, and 5c show the REE pattern for the Spearhead member. (In this type of plot, the abundance of the elements is normalized against chondrite to eliminate the odd-even periodic distribution of the elements.) The stratigraphically lowest sample has the lowest concentration of the light REE and the highest concentration of the heavy REE.

Similarly, in Figures 5a and 5b, the inverse relationship of the light and heavy REE is very striking. This variation can be seen in one outcrop where dark colored pumice has the highest light REE concentration, the highest temperature, 829–904°C, and the lowest concentration of heavy REE. In contrast, the light colored

pumice has the lowest light REE, the highest heavy REE, and the lowest temperature 733–738°C (Figure 5a). This distribution is shown graphically in Figure 6, which shows the concentration of the REEs in the light low-temperature pumice divided by the dark high-temperature pumice. In this figure, Hildreth's data for the upper (high temperature) and lower (low temperature) Bishop Tuff samples are shown for comparison.

This inverse relationship of the light and heavy REE can be shown easily by plotting a light and a heavy REE. Figure 7 contains a plot of La versus Yb for the precaldera lavas, the Rocket Wash member, and the Spearhead member. This inverse relationship of incompatible elements is inconsistent with crystal-liquid equilibrium or the mixing of silicic and mafic liquid. The

Figure 4. Rare earth elements (REEs) for Rocket Wash member.

Figure 5. (a) Rare earth elements for lower part of Spearhead member.

uppermost part of the Spearhead ash-flow sheet has a relatively constant temperature of 868–885°C, whereas the lowest Spearhead has a bimodal temperature distribution.

The variation in major element chemistry of the lavas and two lower ash-flow sheets are shown in Figure 8. Each oxide is plotted against SiO₂ to illustrate the variation with increased evolution of the magma (increasing SiO₂ content). As a group, the lavas contain a much wider range of variation than do the ash flows in all major ele-

ments (Figure 8). The most siliceous part of the lavas overlap with the least siliceous ash flows.

It is instructive to examine the trends of the precaldera Ribbon Cliff lava with the two succeeding ash-flow sheets, the Rocket Wash member, and the Spearhead member. The Ribbon Cliff lavas' range of SiO₂ is 56–71%, whereas the Rocket Wash and Spearhead members' range of SiO₂ is 65–74% (Figure 8). The REE pattern of the Ribbon Cliff lavas show a regular increase

Figure 5. (b) Rare earth elements for upper part of Spearhead member.

in light and heavy REE, with SiO_2 content concomitant with a decrease in Eu (Figure 9).

The Ribbon Cliff lavas most likely represent tapping of the dominant volume of the magma through fractures that intersect the magma chamber. The Rocket Wash and Spearhead ash-flow sheets represent caldera-forming eruptions of the uppermost part of the chamber. The uppermost part of each ash-flow sheet would represent the deepest erupted part of the magma chamber. Conversely, the lowest part of the ash flow represents the top of the chamber.

Figure 7 shows the variation of La and Yb of the Ribbon Cliff lavas and the two overlying ash-flow sheets: the Rocket Wash and Spearhead members. In the lavas, both La and Yb increase with increasing evolution of the liquids. The more silica-rich lavas contain the highest La and Yb and have nearly the same values as the main part of the Rocket Wash member. The upper part of the Spearhead member has the same distribution (with somewhat larger Yb varia-

tion) as the Rocket Wash member and the more evolved lavas of Ribbon Cliff. The lowest part of the Spearhead has the inverse relationship between La and Yb (Figure 7) and the same type of pattern as the lowest samples of the Rocket Wash member.

The pattern of La and Yb is consistent with the following interpretation. The Ribbon Cliff lavas represent magmas of various stages of evolution from the dominant volume of the magma chamber (Smith's 1979 terminology). The Rocket Wash member represents a caldera collapse tapping the highly fractionated top of the chamber. The Rocket Wash ash flows represent a continuing chemical evolutionary pattern from the earlier Ribbon Cliff lavas. The lower-most part of the Rocket Wash ash-flow sheet is the most fractionated, perhaps by liquid-state processes. The Spearhead member represents a larger caldera collapse, with little time between the eruption of Rocket Wash and Spearhead members (Christiansen, 1979). The top part of the Spearhead ash-flow sheet is similar to

Figure 6. Enrichment and depletion for low temperature/high temperature pumice from one outcrop compared to Bishop Tuff. Bishop Tuff samples are from the upper and lower part of the ash flow.

Figure 7. Plots of La versus Yb.

Lower left: precaldera lavas, Rocket Wash and Spearhead members.

Lower right: post Spearhead, pre-Trail Ridge lavas, Trail Ridge ash flows.

Upper right: all of the lavas from Black Mountain.

Figure 8. Major element variation of the Black Mountain volcanics.

the more evolved Ribbon Cliff lavas. The lowest Spearhead ash flows contain a heterogeneous pumice assemblage, and it is these samples that show the inverse relationship between the light and heavy REE. Hildreth (1979, 1981) has interpreted this inverse relationship as indicating liquid-state differentiation.

The Hf and Th variation of this sequence (the Ribbon Cliff lavas and the Rocket Wash and Spearhead ash-flow sheets) can be interpreted in a similar way (Figure 10). The Ribbon Cliff lavas represent a continuing evolution, with Hf and Th increasing with silica content. The Rocket Wash ash flows continue this trend, with the lowest part of the Rocket Wash sheet representing highly evolved liquids. The Hf-Th data for the Spearhead ash flows is somewhat scattered; however, the Hf-Th from the top of the Spearhead ash-flow sheet is similar to the evolved Ribbon Cliff, whereas the lowest Spearhead ash flows represent the highest values of Th and Hf.

A similar but even more striking pattern can be seen in the variation of Eu/Eu(pred) versus Th (Figure 11). Eu(pred)

is the predicted value of Eu if there had been no Eu depletion. It is determined by predicting the abundance of Eu from the abundance of its neighboring rare earth elements, Sm and Tb. Eu/Eu(pred) is a measure of Eu depletion. Again, the main part of the Rocket Wash and upper Spearhead ash-flow sheets contain trends which are similar to the most evolved Ribbon Cliff lavas, whereas the lowest ash flows from the Rocket Wash and Spearhead member represent the most evolved trends (lowest Eu/Eu(pred), highest Th).

Later Evolution*: Post-Spearhead Lavas and Trail Ridge Ash Flows

Between the eruption of the Spearhead ash flows and the Trail Ridge ash flows, the Yellow Cleft lavas and Ring Trachyandesite

* Recent work by Noble et al. (1983) suggests that the time between the Spearhead and Trail Ridge eruptions may be very short, possibly as short as 10^2 to 10^3 years. This interpretation is based on preliminary paleomagnetic pole (TRM) data. This data indicates that both the Spearhead and Trail Ridge ash-flow sheets were erupted during a transitional magnetic period (i.e., between reversals).

Figure 9. Rare earth elements for precaldera lavas (Ribbon Cliff lavas).

were erupted. These are relatively small-volume lavas: the range of the SiO_2 content for Yellow Cleft is 63–70%, and the SiO_2 content of Ring Trachyandesite is 54% (only one sample was used). The SiO_2 range of the Trail Ridge ash flows is 66–72% (Figure 8).

The trends in both the Yellow Cleft lavas and Trail Ridge ash flows show increasing incompatible elements with increasing evolution. With respect to La and Yb (labeled pre-Trail Ridge Lavas in Figure 7), the Yellow Cleft lavas and Ring Trachyandesite values are identical to the lowest values in the Trail Ridge ash flows, and these represent the least evolved samples. In a similar manner, the Hf and Th trends show that the most primitive pre-Trail Ridge (post-Spearhead) lavas are at

the extension of the Trail Ridge trend (Figure 12). The more evolved samples (70% SiO_2) fall within the Trail Ridge trend. In a like manner, the Eu/Eu(pred) versus Th plot of the pre-Trail Ridge lavas shows trends that are continuous with the Trail Ridge ash flow (Figure 11).

The relationship between the Yellow Cleft lavas and the Ring Trachyandesite and Trail Ridge ash flows appears to be similar to the relationship between the Ribbon Cliff lavas and the succeeding ash flows, with one obvious exception. The Trail Ridge ash flows show a systematic increase in incompatible elements with increasing evolution of the magma. There is no inverse relationship of the light REE and heavy REE, which is seen in the Spearhead Sheet. Figure 12 shows the REE enrichment

Figure 11. Eu/Eu(pred)-Th plots for early and later Black Mountain volcanics.

Figure 12. Early/late enrichment for the rare earth elements of the Trail Ridge member. (Compare with Figure 6.)

of a sample from the bottom compared with a sample from the top. This is a distinctly different trend from that observed in the Spearhead ash-flow sheet (compare Figure 12 to Figure 6). Figure 13 shows the overall REE pattern for the Trail Ridge ash flows. Figure 14 shows the pre-Trail Ridge, post-Spearhead lavas.

The data is consistent with the conclusion that the Yellow Cleft lavas and Ring Trachyandesite are sampling the dominant volume of the magma chamber, which has a systematic evolutionary relationship with the Trail Ridge ash flows. The Trail Ridge ash-flow eruptions sample only the top part of the magma chamber. The ash flows of the Trail Ridge do not exhibit the crossover pattern with the REE, such as those present in the early ash flows.

Post-Trail Ridge Magmatic Evolution

The Pillar Springs lava is a relatively large series of lava flows erupted after the Trail Ridge ash-flow eruptions. The SiO_2

content of these lavas ranges from 64–69%. The lavas contain a large range in concentration of the incompatible elements, as well as $\text{Eu}/\text{Eu}(\text{pred})$ values. These incompatible elements increase directly as the evolution of the magmas increase. The Pillar Springs contains the most silicic lavas, and these are highly enriched in incompatibles, and depleted in Eu. (Figures 8, 15–19). These are the most evolved lavas from the Black Mountain center.

The overlying ash-flow sheet is the Gold Flat member. It is also the most highly-evolved peralkaline ash-flow sheet, enriched in incompatible elements. This unit is difficult to sample because it is generally vapor-phase altered. We have one glassy sample from the top of the sheet and two from the base (from Noble et al., 1979). Figure 15 shows the relationship of the REEs in the Pillar Springs lavas and the Gold Flat ash-flow sheet. The top of the Gold Flat sheet is nearly identical to the most fractionated Pillar Springs lava.

The Hidden Cliff lavas form flows that are relatively primitive, with a SiO_2 range of

Figure 13. Rare earth elements plot for Trail Ridge member.

Figure 14. Rare earth elements plot for post-Spearhead, pre-Trail Ridge lavas.

Figure 15. Rare earth elements plot for post-Trail Ridge, pre-Gold Flat lavas, and the Gold Flat ash-flow sheet. Lowest Gold Flat sample is from the top of the ash-flow sheet.

Figure 16. Rare earth elements plot for post-Gold Flat, pre-Labyrinth Canyon lavas.

Figure 17. Rare earth elements plots for the post-Labyrinth Canyon lavas.

Figure 18. $Eu/Eu(pred)$ versus the plots for all of the Black Mountain lavas.

Figure 19. Hf - Th plots for all of the Black Mountain lavas.

55–63%. These lavas contain little variation of the incompatible elements. The Eu/Eu(pred) values range from 0.55–0.84; this represents little evolution of these liquids. Figures 7, 16, 18, and 19 show the La–Yb, REE, Eu/Eu(pred)–Th variation.

Based on this study, the Labyrinth Canyon member is now thought to be part of another volcanic system. This conclusion was discussed in the section entitled “Correlation of Ash-Flow members.”

Model for the Black Mountain Magmatic System

The preliminary data analyses discussed above lead to a simplified model of the Black Mountain magma system. Early evolution of the system is characterized by large, systematic chemical gradients within the magma chamber. The dominant volume, as well as basaltic liquids of the system, have been sampled by the lava flows. Interpretation of these trends suggests an evolutionary pattern dominated by crystal-liquid fractionation, perhaps complemented with limited magma mixing. The upper part of the chamber has erupted as ash-flow tuffs. The ash flows that sampled the deepest levels of the chamber continue the same evolutionary patterns as the lavas. However, the ash-flow sheets that represent the top of the chamber have chemical signatures that contrast with samples from the deeper parts of the chamber. They have elemental patterns inconsistent with crystal-liquid fractionation or magma mixing and may represent liquids generated by thermogravitational diffusion processes.

The later evolution of the magma in the dominant volume (sampled by the lavas) continues the same pattern as the precaldera lavas. The liquids that evolved at the top of the chamber and sampled by the Trail Ridge ash-flow sheet have markedly different trends than the early ash flows. These later ash flows continue the same evolutionary trends as the liquids of the dominant volume and could be the product of crystal liquid processes. In contrast to the early ash flows, there is no evidence in this later ash-flow sheet to support the possibility of thermogravitational diffusion processes.

Coupled interpretation of the inferred temperature data and the trace element

chemical data indicates one plausible mechanism to explain the contrasting patterns between the early and later eruptions. In Table IV the estimated emplacement temperatures for the Spearhead and Trail Ridge ash-flow sheets are shown. The Trail Ridge ash flows are characterized by a lack of low temperatures and a small temperature range. The Spearhead ash flows are characterized by a large range in temperature.

When combined with the previous model of the magma chamber, the following composite picture of the magma system emerges. The early magma chamber sampled by the ash-flow eruptions had greater thermal gradients, lower magma temperatures, and an “anomalous top.” The trace element pattern from this “anomalous top” is consistent with thermogravitational diffusion processes acting to produce a volatile-rich, highly fractionated liquid. Chemical and temperature gradients across this gravitationally stable liquid are recorded in the ash-flow eruption. The large temperature range recorded by the lower Spearhead ash flows documents the thermal gradients present. Thermal gradients at the margin of the chamber, which are necessary to drive Soret diffusion, are presumably maintained by active convection within the central part of the chamber as suggested in Hildreth’s model (1981).

The later eruption is characterized by the lack of extremely low temperatures and a reduced temperature range. The ash flows erupted at this time also show no evidence of thermogravitational diffusion (i.e., no “anomalous top”). Taken together these two observations suggest that a volatile-rich, gravitationally stable liquid did not develop during the later period in a manner similar

to the earlier time period. In contrast, a fractionated body of magma, produced by the same normal crystal-liquid processes presumed to be active in the dominant volume of the chamber, was present at the top of chamber.

These results are broadly consistent with Mahood's (1982) recent suggestion that the early stages of a magmatic system are characterized by high thermal gradients due to intrusion of mafic magmas at the base of the magma chamber. Convection-driven thermogravitational differentiation is maximized under these conditions because convection and Soret diffusion are driven by high thermal gradients. In the later stages, thermal gradients decline and the impact of thermogravitational diffusion is eliminated. This could be due to the fact that the earlier intrusion heated the wall rocks, thereby re-

ducing the magnitude of the thermal contrast produced by the later intrusion. Alternatively, a decline in convective motion within the chamber, plus a transition to conduction-dominated heat transfer, could reduce the marginal temperature gradients in a manner suggested by Walker and Delong (1982). A third alternative is that the time frame between the eruption of the Spearhead ash-flow sheet and the Trail Ridge sheet was too short to allow the development of the volatile-rich, gravitationally stable "cap." This could equally well explain the lack of low temperatures in the Trail Ridge eruption. When the dating of the eruptive units is completed, it will be possible to test this theory. This alternative is supported by the apparent short time-interval between the Spearhead and Trail Ridge members (Noble et al., 1983).

Summary and Conclusions

The Black Mountain volcanic center in southwestern Nevada is a well exposed silicic system characterized by the eruption of several major ash-flow units. These eruptions represent an instantaneous, partial evacuation of a high level magma chamber. They provide us with the opportunity to indirectly observe changing chemical patterns in the magma as it evolved. Documentation of the evolutionary patterns between eruptions in this older center would help to establish petrologic predictions, which could then be tested by CSDP drilling programs at a more recent, active system. Fundamental changes which occur during the evolution of a magma system may be established by comparison of the characteristics of the magma chamber as inferred from early and late eruptions. This type of information will be useful to help to establish the type of magma system to be drilled in order to maximize scientific return. Do we drill a young system or a more mature system in a later stage of development?

To address this question, we have collected stratigraphically controlled samples from the Black Mountain volcanic center.

We have evaluated composition and temperature as a function of stratigraphic position, age relationships, and volume. Our work to date has concentrated on comparing the characteristics of two early ash-flow eruptions with one later eruption. This comparison allows us to contrast the characteristics of a relatively young chamber with a more mature chamber. In the early eruption which sampled the young magma system, we have found relatively complex chemical and temperature variations. Extreme chemical variation of pumice within an outcrop indicates to us that the eruption is tapping different levels of the magma chamber. There is no simple chemical or temperature zonation, and the trends observed at the top of the chamber are not consistent with liquid-crystal equilibrium. In contrast to early eruptions, the trends observed in the later eruption are less complex and are consistent with a relatively simple, partial evacuation of a relatively homogeneous magma chamber. The trends observed in the later eruption are also generally consistent with crystal-liquid fractionation or magma mixing.

The contrasting chemical patterns of the early and late eruptions illustrate that two sequential eruptions of individual cooling units from the same volcanic center can take different evolutionary paths. This may reflect a natural evolutionary trend associated with changing temperature and volatile gradients within the chamber as it matures.

We have also shown that chemical variability in eruptive units can be used to determine the stratigraphic continuity of an eruption from a volcanic center. Significant differences in chemical variation occur from one ash-flow sheet to another, especially in the trace element content. Using the chemical signatures, we have demonstrated that the Spearhead member in Civet Cat Canyon is distinctively different from the Spearhead member in Thirsty Canyon. We have also

documented that the Labyrinth Canyon ash-flow member of the Thirsty Canyon Tuff has a chemical composition decidedly different from the other trends of the Thirsty Canyon Tuff. Comparison of the Spearhead ash-flow sheet of Civet Cat Canyon with the Labyrinth Canyon ash-flow sheet reveals similar chemical signatures. This suggests that perhaps these two units are related and come from a nearby volcanic center, possibly the Stonewall Mountain center (Noble et al., 1983). This type of analysis suggests that chemical variability can be used to evaluate field correlations, and can constrain models based on field relationship. This type of approach could be valuable in assessing the lateral continuity of a potential medium for nuclear testing.

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Appendix A.
Tables II, III, and IV

Table II. Samples of Black Mountain volcanic center.

Sample No.	Field No.	Field description
Post Thirsty Canyon Basalt (Lavas)		
61	TBMB	(No majors)
57	N-95	
60	OPT-10	
Labyrinth Canyon (Ash flow)		
53	TL-1-1	(Base)
36	TL-1-2	
35	TL-1-3	
Hidden Cliff (Lavas)		
3	63C-22	
49	63C-23	
4	63C-23	
10	BM-11	
113	BM-25	(No INAA)
Gold Flat		
15	TTG-1-1	(Top)
Pillar Springs (Lavas)		
114	N-143	(Upper) (No INAA)
115	N-89	(Upper) (No INAA)
52	NRG	(Upper)
2	4S-9	(Middle)
42	LPS-V	(Middle)
116	BM-23	(Middle) (No INAA)
117	BMR-4	(Middle) (No INAA)
8	N-83	(Lower)
63	N-122	(Lower)
65	MF-B	(Lower)
66	TP-20-C	(Lower)
Basalt Flow		
58	B-TT-TG	
Trail Ridge (Ash flows)		
1	4S-6	(Upper)
12	SSM-1	(Middle)
51	SSM-2	(Middle)
46	TT-EBM	(Middle)
25	S-3-1	(Blobs) Base above air fall, leached sample
26	S-3-1	(Blobs) Base above air fall, unleached sample
27	S-3-2	(Blobs) Base above air fall
30	S-3-4	(Pum.) Base above air fall
37	S-3-5	(Pum.) Base above air fall
33	S-3-6L	(Pum., mixed, light part)
32	S-3-6D	(Pum., mixed, dark part)
62	TC-T	(Lower)
16	TR-BLOB	(Base)
17	TR-Dev	(Base, devitrified blob)
55	TR-2-1LT	(Pum., air fall bimodal, light)
54	TR-2-1-DK	(Pum., air fall bimodal, dark)
18	TR-VIT Vitrophyre-base	
103	TR-VIT2 Vitrophyre-base	
104	TR-Rec Devitrified above TR-VIT2	

Table II. (Continued.)

Sample No.	Field No.	Field description
108	TR-BOT-FL Blobs from lower flow	
109	TR-UP- BL Blobs from overlying flow	
109.1	Replicate of 109	
109.2	Replicate of 109	
109.3	Replicate of 109	
109.4	Replicate of 109	
106	TR-10-2	Glassy tuff (Middle-flow, Lower part Civet Cat Canyon)
105	TR-10-1	Dev. tuff above last sample
107	TR-11-1	Blob-Lithic Rich Zone (S. Stonewall Mt.)
110	TR-12-1	Blob-Lithic free zone above last sample
43	U20K-TO	Lithic
44	3N-GV	Lithic
Basalt Flow		
59	B-TS-TT	
Yellow Cleft (Lava)		
5	N-38	
9	3F-44	
47	BM-64-101B	
Ring Trachyandesite		
11	PSB	
Spearhead (Ash-flows)		
North-Civet Cat Canyon Area		
56	S-7-3	Top, pum. in flow
38	S-7-4	Top, pum. in flow
38.1	S-16-2	Top, pum. in flow (No INAA)
95	S-16-3	Top, pum. in flow
81	S-16-4	Top, pum. in flow
80	S-16-1	Dev. tuff, above air fall
13	TTSU-HGU	Glass, tuff, above air fall
40	S-7-1	Air fall tan
72	S-15A	Air fall tan
73	—	Air fall white, lowest
Nellis Range, East of St. Helens		
82	S-17-1	Top pum.
83	S-17-1	Duplicate analysis
84	S-17-2	Top pum.
85	S-17-5	Top pum.
86	S-17-6	Top pum.
96	S-17-8	Tob blobs
97	S-17-9	Top blobs
87	S-18-1	Top pum. (dark)
88	S-18-2	Top pum. (gray)
89	S-19-2	Hydrated glass, base
90	S-19-2A	Nonhydrated glass, base
39	S-6-1	Air fall NE Black Mountain
South Stonewall Mountain		
91	S-20-1	100 ft above air fall
92	S-20-2	Base, above air fall

Table II. (Continued.)

Sample No.	Field No.	Field description
East Fork Thirsty Canyon		
94	S-14-1	Dev. blob top no majors
79	S-14-1A	Dev. blob top
77	S-10-1	Blob above air fall
74	S-11-1	Pum. above air fall
78	S-12-1	Pum. rich flow above air fall
76	S-11-3	Air fall above surge
75	S-11-2	Air fall below surge
Lower Thirsty Canyon (upper flow)		
22	S-2-1	Blobs, base
23	S-2-5	Blobs, base
24	S-2-6	Blobs, base
67	S-2-9	Pum. base
68	S-2-10	Pum. base
69	S-2-13	Pum. base
70	S-2-13A	Pum. base
71	S-2-14	Pum. base
28	S-4-1	Blob, base
41	S-5-1	Glassy tuff, base
Lower Thirsty Canyon (lower flow)		
29	S-1-1	Pum. base
19	S-1-3	Pum. base
20	S-1-7	Pum. base
21	S-1-8	Pum. base
31	S-1-9	Pum. base
45	TTSI-4	Lithic
Rocket Wash		
34	RW-1-1	Base, over basement (basalt) high (carbonate contam.)
98	RW-2-1	Air fall pum.
99	RW-2-2	Base above air fall
100	RW-3-1	Dev. tuff
101	RW-4-2	Dev. tuff
102	RW-4-1	Dev. tuff
Ribbon Cliff (Precaldera lavas)		
7	N-64	(Upper)
6	N-61	(Upper)
48	N-67	(Upper)
50	63C-46	(Lower)
14	UE-20J498	(Lower)
93	TC-8	(Lower)
64	UE-20K-221	(Lower)

Table IIIa. Major elements (anhydrous).

ID	SiO2	Al2O3	Fe2O3	CaO	MgO	TiO2	MnO	Na2O	K2O	P2O5
1.	67.46	16.48	2.53	1.21	.40	.49	.12	5.03	6.17	.11
2.	69.90	14.79	3.29	.66	.23	.36	.16	5.14	5.42	.05
3.	55.46	17.01	7.64	5.87	3.23	1.31	.17	4.76	3.84	.71
4.	58.93	17.05	5.29	2.85	4.29	.93	.14	5.03	4.93	.55
5.	63.43	18.04	3.52	2.33	1.01	.71	.15	5.07	5.37	.37
6.	66.38	17.30	3.12	1.01	.51	.52	.16	5.36	5.46	.18
7.	71.74	14.63	2.44	.20	.28	.24	.15	4.88	5.39	.05
8.	64.44	17.02	4.18	2.03	.88	.89	.14	4.96	5.07	.39
9.	69.93	15.03	3.19	.68	.32	.42	.17	5.25	4.74	.27
10.	63.94	17.73	4.09	2.46	.92	.78	.12	4.92	4.71	.33
11.	54.52	17.66	8.49	6.53	2.67	1.91	.16	4.15	3.09	.82
12.	73.63	13.54	2.09	.71	.05	.15	.08	4.36	5.38	.01
13.	76.02	12.33	1.73	.36	.09	.11	.07	4.45	4.83	0.00
14.	61.55	18.04	4.86	3.23	1.05	.90	.12	5.26	4.65	.34
15.	65.29	15.48	4.54	1.64	.31	.31	.14	6.41	5.80	.08
16.	67.51	15.55	3.61	.85	.25	.42	.18	5.83	5.76	.04
17.	66.86	15.93	3.97	.49	.21	.37	.20	6.30	5.64	.02
18.	67.01	15.78	3.65	.95	.36	.45	.18	5.48	6.10	.05
19.	74.05	12.74	2.33	.26	.11	.14	.08	3.91	6.38	.01
20.	73.05	13.10	2.47	.34	.14	.15	.09	4.14	6.52	.01
21.	73.54	12.85	2.49	.38	.31	.15	.09	4.08	6.12	.01
22.	66.09	15.72	3.98	.96	.29	.44	.20	5.50	6.78	.04
23.	67.06	15.16	4.14	.86	.16	.38	.21	5.82	6.19	.02
24.	68.47	14.43	3.88	.84	.21	.34	.19	5.38	6.24	.02
25.	65.96	16.20	3.72	.84	.33	.43	.19	5.92	6.37	.04
26.	67.02	15.64	3.64	1.29	.33	.42	.18	5.63	5.82	.04
27.	66.62	16.03	3.60	.83	.30	.43	.18	5.82	6.16	.04
28.	65.97	15.94	4.11	1.18	.38	.44	.19	5.17	6.58	.05
29.	74.10	12.40	2.30	.59	.29	.14	.08	4.41	5.68	.01
30.	66.20	15.74	3.95	.93	.44	.35	.20	5.46	6.70	.02
31.	73.36	13.07	2.37	.20	.20	.15	.08	4.03	6.53	.01
32.	64.84	16.47	3.84	1.35	.35	.42	.19	5.71	6.79	.04
33.	67.62	14.92	3.82	.92	.21	.31	.19	5.63	6.37	.01
34.	47.66	8.72	1.77	34.35	.48	.17	.08	3.08	3.63	.08
35.	74.01	13.06	2.23	.31	.31	.14	.08	3.52	6.34	.01
36.	75.57	11.98	2.26	.41	.08	.12	.07	3.80	5.71	.01
37.	66.14	16.15	3.77	.81	.51	.39	.19	5.33	6.68	.03
38.	75.20	12.37	2.03	.86	.14	.12	.07	4.04	5.17	.01
39.	70.11	15.23	3.14	.24	.43	.21	.10	3.67	6.84	.02
40.	75.51	13.04	2.20	.32	.12	.13	.07	4.13	4.47	.01
41.	69.47	15.11	3.04	.31	.17	.29	.14	5.59	5.86	.01
42.	69.26	14.39	3.90	.72	.21	.36	.16	5.08	5.90	.02
43.	72.17	12.66	3.59	.48	.06	.25	.12	5.78	4.88	.01
44.	74.86	12.39	2.91	0.00	.04	.17	.09	4.93	4.59	.02
45.	75.31	12.33	2.12	.28	.02	.13	.08	4.93	4.80	.01
46.	71.52	13.83	2.76	.60	.25	.22	.09	4.61	6.12	.02
47.	64.66	17.84	3.01	1.22	.66	.74	.16	5.37	6.08	.26
48.	70.27	16.03	2.46	.28	.28	.30	.14	4.84	5.34	.06
49.	63.29	17.98	5.32	2.60	1.04	.86	.12	3.27	4.99	.54

Table IIIa. (Continued.)

ID	SI02	AL203	FE203	CAO	MGO	TIO2	MNO	NA2O	K2O	P2O5
50.	62.68	17.70	4.59	2.88	.88	.84	.10	5.23	4.77	.32
51.	73.49	13.61	1.98	.81	.15	.15	.08	4.40	5.32	.01
52.	68.46	15.13	3.21	1.28	.39	.40	.12	4.62	6.30	.07
53.	75.38	12.33	2.04	.34	.14	.12	.07	3.48	6.08	.01
55.	72.34	12.79	3.65	.42	.56	.23	.11	4.21	5.70	.01
54.	69.61	16.06	2.58	.79	1.43	.40	.13	4.43	4.54	.03
56.	70.17	13.38	2.48	4.70	.71	.29	.08	3.51	4.60	.08
57.	61.99	17.61	5.78	2.55	1.02	.33	.12	5.19	4.89	.53
58.	48.40	18.38	11.18	8.99	5.41	1.84	.35	3.17	1.53	.78
59.	60.52	18.68	5.34	2.54	1.12	.59	.53	5.59	4.47	.63
60.	51.77	17.59	9.69	6.66	4.57	1.79	.19	4.07	2.68	.99
62.	67.24	16.04	3.78	.79	.58	.39	.19	5.35	5.55	.09
63.	66.33	16.48	3.67	1.64	.52	.76	.07	5.12	5.12	.29
64.	67.24	15.49	3.31	1.39	.51	.63	.15	5.67	5.37	.24
65.	64.34	17.35	3.97	2.22	.99	.83	.12	4.84	4.94	.40
66.	64.15	16.54	4.79	2.33	1.01	.91	.14	4.67	5.07	.39
67.	73.92	12.79	2.33	.36	.29	.15	.09	4.50	5.55	.03
68.	73.93	12.90	2.28	.38	.68	.15	.08	4.39	5.18	.03
69.	74.01	12.68	2.26	.44	.69	.15	.09	4.57	5.10	.03
70.	73.75	12.95	2.29	.45	.59	.15	.09	4.57	5.15	.02
71.	66.86	15.48	3.93	.97	.66	.45	.17	5.50	5.90	.07
72.	74.18	12.94	2.17	.43	.11	.14	.07	4.29	5.64	.03
73.	72.92	13.71	2.41	.48	.08	.15	.10	5.05	5.09	.02
74.	69.92	14.90	3.02	.60	1.56	.31	.17	4.89	4.58	.06
75.	69.91	15.20	2.89	.85	.97	.33	.11	4.80	4.86	.08
76.	70.03	14.41	3.22	.97	1.14	.57	.13	4.71	4.70	.13
77.	69.12	14.50	3.24	1.08	.52	.56	.13	5.22	5.48	.14
78.	69.01	14.50	3.04	1.59	.36	.30	.14	4.17	6.82	.06
79.	65.87	15.61	3.65	1.18	.48	.48	.17	6.14	6.32	.11
80.	71.41	14.36	2.40	.42	.05	.16	.09	5.37	5.70	.03
81.	74.35	13.05	2.15	.37	.04	.13	.08	4.26	5.57	.02
82.	71.85	12.20	3.43	.51	.20	.24	.16	4.82	6.57	.03
84.	72.63	12.24	3.44	1.05	.21	.23	.14	4.24	5.80	.03
85.	73.57	12.01	3.38	.50	.29	.21	.14	4.26	5.59	.05
86.	71.28	13.15	3.49	.82	.12	.30	.19	5.20	5.41	.04
87.	73.30	12.13	3.45	.39	.07	.22	.15	4.88	5.38	.02
88.	70.53	13.60	3.83	.91	.52	.35	.20	4.53	5.46	.08
89.	71.88	10.85	1.97	6.26	.19	.13	.07	4.15	4.45	.05
90.	76.40	11.46	2.07	.39	.02	.12	.08	4.66	4.80	.02
91.	76.62	11.57	2.03	.25	.05	.12	.07	3.57	5.69	.02
92.	76.22	12.13	2.08	.57	.18	.12	.08	3.69	4.91	.02
93.	56.05	19.00	6.78	6.09	1.65	1.55	.18	4.86	2.89	.95
95.	75.26	12.51	2.09	.45	.05	.13	.08	4.00	5.42	.02
96.	71.10	13.31	3.46	.73	.07	.28	.15	5.38	5.50	.03
97.	71.02	13.34	3.52	.70	.09	.31	.19	5.41	5.39	.04
98.	73.78	12.54	2.04	1.66	.02	.09	.06	4.76	5.04	.02
99.	67.85	12.56	2.76	6.63	.26	.26	.13	4.91	4.53	.10
100.	71.97	13.40	2.99	.63	.21	.31	.13	5.19	5.11	.07
101.	72.48	13.39	2.78	.53	.22	.29	.12	5.04	5.09	.06
102.	72.19	13.22	2.93	.75	.28	.31	.15	4.96	5.14	.07
103.	68.86	14.73	3.37	.84	.33	.42	.17	5.44	5.75	.08

Table IIIa. (Continued.)

ID	SiO2	Al2O3	Fe2O3	CaO	MgO	TiO2	MnO	Na2O	K2O	P2O5
104.	68.39	14.96	3.39	.69	.24	.44	.18	6.04	5.59	.09
105.	72.33	13.73	2.19	.94	.18	.28	.09	4.81	5.40	.06
106.	72.53	13.22	2.06	1.76	.16	.23	.10	4.87	4.98	.08
107.	67.54	15.64	3.01	1.40	.42	.48	.13	4.99	6.28	.13
108.	72.92	12.29	3.39	.28	.05	.21	.14	5.31	5.38	.02
109.	69.14	14.38	3.66	.73	.25	.35	.21	5.84	5.38	.05
110.	73.03	13.36	1.90	1.12	.09	.15	.08	4.87	5.39	.03
113.	60.70	17.47	5.82	2.63	1.41	.93	.18	5.45	4.95	.46
114.	67.34	15.99	3.29	1.42	.64	.60	.11	5.03	5.41	.17
115.	70.24	15.89	2.55	.49	.40	.34	.10	4.65	5.26	.08
116.	69.09	15.47	3.27	.40	.21	.38	.17	5.29	5.70	.02
117.	69.31	15.40	3.10	.76	.27	.34	.13	5.03	5.63	.04
118.	73.37	13.45	2.62	.45	.25	.22	.12	3.41	6.07	.04

Table IIIb. Rare earth elements (INAA).

I.D.	LA	CE	SM	EU	TB	YB	LU
1.0	74.2	131.2	9.2	2.05	1.0	4.1	.6
2.0	245.5	451.5	22.5	.65	2.6	13.9	2.5
3.0	82.9	153.9	8.5	2.17	1.1	4.2	.3
4.0	114.1	201.8	11.8	1.87	1.3	5.4	.3
5.0	77.1	144.5	8.9	2.72	.9	3.2	.3
6.0	103.5	189.4	9.3	2.35	1.1	4.8	.9
7.0	161.1	283.4	15.3	.47	1.5	6.9	1.2
8.0	114.3	196.7	13.2	2.57	1.3	5.2	.7
9.0	112.6	211.8	11.9	1.02	1.3	6.1	1.1
10.0	107.0	198.6	12.8	2.64	1.3	5.1	.9
11.0	71.5	135.9	10.9	2.88	1.1	3.6	.4
12.0	107.8	194.5	11.8	.16	1.3	6.1	1.1
13.0	65.2	93.5	10.6	.04	1.6	7.4	1.3
14.0	106.4	201.1	9.5	2.33	1.2	5.4	.4
15.0	229.9	438.2	25.4	.89	3.5	19.9	3.5
16.0	145.0	279.3	16.1	.73	1.4	6.3	1.2
17.0	247.8	438.1	18.7	.47	1.7	7.0	1.4
18.0	155.5	275.9	13.0	.81	1.4	6.5	1.2
19.0	97.9	189.9	14.1	.06	2.2	11.4	2.1
20.0	102.6	195.6	14.6	.07	2.1	11.1	2.0
21.0	96.4	207.0	14.4	.06	2.2	11.8	2.3
22.0	453.9	795.6	27.7	.37	1.9	6.9	1.3
23.0	365.2	639.0	26.5	.25	2.1	8.0	1.1
24.0	356.4	612.6	25.6	.21	2.0	7.9	1.5
25.0	161.5	296.9	15.0	.69	1.5	6.8	1.3
26.0	151.2	281.6	13.8	.66	1.4	6.3	1.2
27.0	148.1	267.5	13.9	.74	1.3	5.3	1.1
28.0	298.9	498.3	22.3	.63	1.7	7.2	1.4
29.0	113.3	222.2	15.0	.06	2.2	11.6	2.1
30.0	290.9	447.3	21.0	.43	1.8	7.8	.3
31.0	101.2	207.4	14.1	.08	2.2	12.0	2.2
32.0	155.9	283.4	13.4	.62	1.4	6.1	1.1
33.0	248.9	441.4	20.3	.34	2.0	9.0	1.8
34.0	123.5	198.3	11.2	.19	1.2	6.1	1.2
35.0	80.5	151.1	11.3	.04	1.5	7.3	.8
36.0	80.6	172.3	11.5	.02	1.6	7.2	1.3
37.0	189.8	306.6	15.4	.54	1.4	6.7	1.4
38.0	76.4	155.8	11.0	.02	1.6	7.2	1.3
39.0	118.2	207.1	15.5	.20	2.2	10.7	1.9
40.0	72.3	132.9	10.7	.03	1.5	7.0	1.2
41.0	166.9	308.2	15.1	.30	1.7	8.4	1.5
42.0	255.9	428.8	21.1	.41	2.5	13.1	2.3
43.0	207.7	377.5	21.5	.21	2.9	14.2	1.6
44.0	122.0	265.6	17.3	.11	2.2	10.3	1.8
45.0	76.6	143.8	13.1	.04	1.6	7.6	1.4
46.0	93.9	199.0	13.7	.15	2.1	11.8	1.6
47.0	82.3	147.8	8.5	3.38	1.0	3.5	.0
48.0	158.4	269.3	12.3	.68	1.3	6.3	1.3

Table IIIb. (Continued.)

I.D.	LA	CE	SM	EU	TB	YB	LU
49.0	94.2	181.4	11.2	2.25	1.4	6.3	1.0
50.0	109.0	194.8	11.7	2.35	1.2	5.1	.9
51.0	104.8	185.7	11.8	.15	1.4	6.4	1.3
52.0	155.9	284.4	13.2	.98	1.5	8.6	1.4
53.0	77.1	148.3	11.7	.03	1.6	7.0	1.2
54.0	159.9	288.8	20.1	.41	2.6	12.7	2.3
55.0	147.6	266.4	13.4	1.93	1.3	5.9	1.0
56.0	73.8	138.9	8.7	.65	1.0	3.7	.5
57.0	49.8	103.6	9.9	2.74	1.1	3.5	.5
58.0	53.0	115.7	8.3	2.43	.8	2.5	.4
59.0	104.0	155.6	7.7	2.00	.7	3.7	.6
60.0	105.6	188.1	11.5	2.47	1.3	5.4	.5
61.0	83.5	162.5	8.7	2.66	.7	2.1	.4
62.0	174.4	300.6	14.4	.87	1.5	6.4	.5
63.0	80.1	140.6	9.1	2.62	.9	2.9	.5
64.0	159.8	298.6	14.6	2.56	1.7	7.8	1.4
65.0	123.3	238.0	10.6	2.84	1.4	6.0	.4
66.0	131.3	222.3	15.4	3.16	1.5	6.1	.9
67.0	123.8	275.8	17.7	.08	2.5	13.5	2.5
68.0	110.1	207.2	15.5	.07	2.3	11.5	2.0
69.0	134.5	245.7	16.4	.07	2.3	12.7	2.3
70.0	116.2	238.9	15.6	.06	2.3	12.2	2.2
71.0	420.0	694.0	27.2	.46	2.2	7.7	1.5
72.0	79.0	147.5	9.7	.03	1.7	7.5	1.3
73.0	104.0	192.5	13.4	.05	1.5	7.0	1.3
74.0	175.4	395.7	16.7	.36	1.8	8.8	1.6
75.0	109.8	190.4	11.0	1.41	1.2	5.4	.9
76.0	130.2	264.3	12.9	1.39	1.4	6.9	1.3
77.0	146.2	251.9	8.1	1.55	1.5	6.6	1.1
78.0	164.7	309.9	16.9	.31	1.9	9.0	1.6
79.0	190.3	333.3	18.3	.63	1.4	5.0	.9
80.0	80.4	156.2	11.9	.06	1.6	6.7	1.2
81.0	81.6	166.8	11.4	.02	1.7	7.9	1.5
82.0	175.8	341.7	19.6	.24	2.7	12.7	2.4
83.0	176.7	333.7	20.8	.25	2.7	13.4	2.5
84.0	198.5	374.5	19.2	.26	2.6	12.9	2.5
85.0	186.4	332.3	20.0	.25	2.6	12.4	2.4
86.0	320.0	605.1	26.3	.42	2.2	9.5	2.0
87.0	186.6	339.3	20.7	.25	2.6	12.4	2.2
88.0	325.5	589.7	22.1	.36	2.1	8.8	1.9
89.0	92.8	184.8	13.5	.05	2.0	10.8	1.9
90.0	93.3	205.1	15.3	.05	2.3	12.4	2.2
91.0	59.1	116.9	6.8	.03	1.6	6.8	1.1
92.0	70.6	145.9	11.2	.02	1.6	7.4	1.3
93.0	77.6	156.1	12.4	4.18	1.2	4.0	.7
94.0	170.3	290.3	14.4	.53	1.1	4.6	.9
95.0	46.4	111.1	7.3	2.08	1.4	6.6	.9
96.0	281.2	450.2	20.7	.26	1.8	8.1	1.6
97.0	293.4	526.6	13.0	.30	1.8	8.3	1.6
98.0	51.3	103.7	9.5	.04	3.1	15.8	2.6
99.0	155.2	292.3	15.3	.25	1.9	9.3	1.8

Table IIIb. (Continued.)

I.D.	LA	CE	SM	EU	TB	YB	LU
100.0	175.1	313.6	16.3	.46	1.7	7.9	1.5
101.0	180.7	355.0	16.7	.45	1.7	7.8	1.2
102.0	112.7	266.0	11.8	.54	1.6	7.0	1.0
103.0	160.8	287.0	14.4	.90	1.4	6.2	.8
104.0	157.9	277.9	15.5	.92	1.4	6.2	1.1
105.0	102.7	164.4	10.0	.78	1.2	5.1	.9
106.0	98.8	176.8	11.2	.42	1.3	5.9	1.1
107.0	115.0	211.5	10.2	1.31	.9	3.8	.3
108.0	171.7	281.6	20.1	.22	2.5	11.7	2.4
109.0	265.1	470.9	19.9	.42	1.8	7.7	1.5
110.0	111.6	204.1	12.6	.10	1.4	6.2	1.2

Table IIIc. Trace elements (INAA).

I.D	SC	ZN	RB	SB	CS	HF	TA	TH
1.0	7.7	82.4	118.3	.3	2.2	16.1	1.7	11.5
2.0	5.3	188.0	314.0	.6	5.4	31.0	7.3	53.1
3.0	14.0	98.2	81.2	1.0	.4	10.3	1.8	9.5
4.0	8.4	123.3	123.1	.2	.7	14.1	2.7	17.7
5.0	10.5	121.2	84.2	1.0	1.0	10.3	1.5	8.5
6.0	8.3	119.8	124.3	.3	.9	16.1	2.3	14.3
7.0	4.4	104.9	216.7	.5	1.4	16.7	4.1	31.3
8.0	8.7	110.6	127.6	.3	1.2	15.8	2.4	17.0
9.0	5.4	123.5	164.2	.5	1.8	17.9	3.4	20.7
10.0	7.5	113.8	124.1	.3	1.6	16.8	2.9	19.1
11.0	14.4	111.4	67.6	.2	1.1	9.3	1.5	9.2
12.0	4.8	68.7	223.8	1.4	4.3	11.6	3.0	22.0
13.0	.9	136.4	245.4	.9	4.6	13.2	4.4	21.7
14.0	6.6	111.4	134.4	.3	1.4	15.8	2.7	18.9
15.0	1.9	260.4	403.3	.8	6.2	55.9	12.8	75.3
16.0	10.4	139.2	124.7	.2	1.9	22.2	2.4	16.3
17.0	8.8	137.9	147.5	.3	1.6	24.2	3.2	23.4
18.0	9.8	142.6	125.3	.2	1.9	21.6	18.7	17.0
19.0	1.4	140.8	474.2	.6	7.8	20.9	8.7	42.2
20.0	1.5	153.3	396.2	.6	6.6	21.0	6.2	41.5
21.0	1.6	170.3	400.9	.6	8.7	22.0	6.4	42.7
22.0	15.1	139.9	150.0	.2	1.8	26.5	6.3	35.7
23.0	11.0	133.5	193.3	.2	2.2	26.5	3.6	38.8
24.0	9.6	127.4	181.1	.2	2.3	24.4	3.6	37.8
25.0	9.6	138.8	134.6	.3	2.0	22.2	5.2	17.9
26.0	8.9	132.9	122.9	.2	2.0	21.3	2.7	17.2
27.0	10.0	144.0	129.5	.2	1.9	20.8	5.9	16.3
28.0	10.2	128.8	163.6	.2	2.3	23.4	3.1	30.9
29.0	1.6	173.9	389.5	.6	7.6	22.3	8.6	43.4
30.0	9.1	158.1	162.9	.3	2.8	24.6	3.3	25.3
31.0	1.5	166.5	432.3	.6	7.1	21.7	9.5	43.4
32.0	10.3	150.4	129.0	.3	2.0	22.0	2.7	17.0
33.0	6.6	157.0	194.0	.4	3.4	26.4	11.0	28.8
34.0	2.9	98.1	180.6	.3	2.9	12.1	2.8	21.5
35.0	1.1	148.3	253.2	.7	5.0	14.9	5.9	22.3
36.0	1.0	150.1	250.5	.7	4.6	14.3	3.8	21.6
37.0	9.2	132.6	135.1	.3	2.3	21.7	2.6	19.4
38.0	1.0	139.5	254.0	.9	5.1	14.2	4.6	21.8
39.0	2.6	208.0	321.5	.6	5.4	22.2	7.8	42.0
40.0	1.2	224.6	246.6	.7	7.4	14.6	5.0	21.6
41.0	4.5	150.4	250.2	.4	2.3	19.0	9.3	34.0
42.0	5.1	199.6	279.1	.7	5.4	29.4	6.9	50.2
43.0	1.4	200.9	283.5	.7	5.0	38.3	7.3	41.4
44.0	.4	281.3	375.1	.5	4.5	36.8	33.3	41.7
45.0	.5	159.4	225.0	.3	3.5	18.1	3.6	20.1
46.0	2.1	150.7	312.4	.6	5.3	20.5	7.9	37.6
47.0	8.6	99.5	82.2	.2	.6	10.0	1.6	5.7
48.0	4.7	130.8	197.8	.5	1.6	17.6	4.7	29.9

Table IIIc. (Continued.)

I.D	SC	ZN	RB	SB	CS	HF	TA	TH
49.0	9.2	111.9	109.2	1.0	1.3	12.5	3.1	13.1
50.0	6.9	131.2	145.8	.2	1.5	16.8	4.5	17.4
51.0	4.7	89.0	227.4	2.4	7.5	11.5	3.0	22.8
52.0	4.1	139.4	218.1	.5	4.0	19.2	4.5	38.4
53.0	1.1	138.4	256.5	.7	4.9	14.9	6.4	21.0
54.0	1.1	223.5	283.7	.7	7.8	35.8	7.8	41.3
55.0	4.3	128.3	151.9	.5	8.8	17.3	2.5	21.9
56.0	5.0	131.2	149.5	1.1	3.6	12.1	2.2	12.1
57.0	19.7	219.0	29.4	.3	1.0	6.5	1.8	3.5
58.0	20.4	141.4	31.6	.1	1.0	5.6	1.0	3.8
59.0	2.8	227.7	107.6	3.5	.7	15.1	40.3	13.0
60.0	7.9	145.1	138.9	.5	1.2	18.0	2.6	18.3
61.0	15.2	135.8	38.9	2.0	2.2	8.2	1.2	8.5
62.0	9.0	152.0	136.8	.3	1.9	21.0	10.9	19.1
63.0	16.2	237.4	57.2	.1	.7	8.0	2.3	4.2
64.0	9.1	176.9	193.9	.6	1.4	22.5	3.4	26.3
65.0	10.1	118.5	152.7	1.2	1.2	18.4	2.6	19.5
66.0	11.6	145.5	151.0	1.3	1.3	18.0	2.6	19.7
67.0	1.8	210.2	396.8	.7	6.6	25.4	7.6	49.2
68.0	1.7	177.3	390.0	.6	7.8	24.7	7.1	47.1
69.0	1.7	173.7	383.3	.6	7.8	25.5	7.4	48.8
70.0	1.9	172.0	377.9	.6	7.2	24.2	7.1	46.3
71.0	15.2	163.2	188.6	.3	2.4	29.1	3.3	35.2
72.0	1.3	101.3	181.0	.8	9.0	13.6	3.5	22.9
73.0	1.3	143.6	215.0	.3	3.5	18.9	3.2	20.8
74.0	5.9	189.3	313.8	.6	9.2	22.8	5.0	36.4
75.0	6.2	128.3	182.4	.3	8.5	18.1	2.7	21.3
76.0	6.2	142.9	223.3	.5	5.1	20.8	3.5	26.8
77.0	6.6	117.8	159.7	.3	2.6	19.5	3.3	25.3
78.0	5.2	168.3	295.3	.5	4.0	20.9	4.6	34.8
79.0	13.8	133.5	134.4	.3	1.4	25.1	2.1	19.2
80.0	1.3	130.9	259.1	.5	2.8	16.3	3.6	23.0
81.0	1.0	119.1	266.2	.7	5.1	15.5	3.7	23.8
82.0	2.0	227.8	288.8	.7	5.2	35.5	6.3	40.5
83.0	2.1	203.3	291.7	.7	5.2	36.1	7.4	41.1
84.0	2.2	232.6	247.1	.7	5.1	35.6	6.4	35.9
85.0	2.4	228.9	283.8	.6	5.0	35.0	5.7	39.9
86.0	8.4	169.2	183.3	.3	2.8	27.0	3.8	30.2
87.0	2.3	226.7	284.7	.7	5.2	35.5	5.8	39.5
88.0	9.0	164.5	170.4	.5	3.7	26.2	3.8	30.9
89.0	1.4	184.5	298.6	.6	5.1	20.1	5.9	39.4
90.0	1.2	176.8	371.7	.7	6.2	21.3	6.9	44.2
91.0	1.2	138.9	242.2	.7	4.8	14.5	3.3	22.1
92.0	1.0	148.5	233.6	.7	4.3	14.9	3.5	22.3
93.0	13.3	134.0	60.4	3.3	.2	8.7	1.3	5.8
94.0	11.9	112.6	113.0	.2	1.1	21.3	1.9	15.9
95.0	1.1	116.4	227.2	.6	4.3	12.9	3.1	19.7
96.0	6.0	146.3	153.2	.3	2.4	23.0	3.2	25.9
97.0	7.0	145.5	153.2	.3	2.3	23.1	3.3	25.6
98.0	.2	236.5	496.7	.8	7.5	29.4	9.8	51.3
99.0	4.3	148.1	268.2	.4	4.0	18.0	4.1	32.0

Table IIIc. (Continued.)

I.D	SC	ZN	RB	SB	CS	HF	TA	TH
100.0	5.5	149.3	215.0	.4	2.5	19.6	4.0	31.9
101.0	5.9	145.4	221.8	.8	2.4	19.7	4.0	31.6
102.0	5.2	130.8	202.4	.4	1.8	17.0	3.8	30.6
103.0	9.5	128.4	123.4	.2	1.7	20.4	2.5	16.6
104.0	10.4	132.8	131.4	.2	1.8	20.8	2.4	16.6
105.0	6.0	93.9	179.8	.5	2.4	13.0	2.4	18.4
106.0	5.7	110.2	195.0	.8	5.2	13.0	2.4	19.3
107.0	12.3	90.0	100.5	.3	1.3	15.3	1.4	9.7
108.0	1.9	213.1	279.5	.6	5.3	33.6	5.8	38.2
109.0	9.2	151.5	150.6	.3	2.3	23.6	3.1	24.1
110.0	4.5	94.6	217.2	.6	3.4	11.4	2.9	23.0
118.0	4.9	134.1	377.6	.6	5.3	23.6	6.3	45.7

Table IIIId. Trace elements (ICP).

I.D.	BE	CO	CU	PB	NI	SR	ZR	V	ZN
4.0	11.5	7.0	4.8	35.0	58.0	12.7	558.0	.8	132.0
12.0	5.4	18.0	4.3	15.0	90.0	18.4	24.0	4.3	54.0
15.0	20.2	13.0	4.2	55.0	6.0	150.0	2080.0	7.4	222.0
16.0	3.3	16.0	1.8	10.0	48.0	6.7	966.0	3.9	116.0
17.0	4.6	4.0	3.2	15.0	32.0	4.3	948.0	3.3	102.0
18.0	3.6	10.0	****	15.0	8.0	12.0	948.0	5.3	105.0
19.0	11.7	15.0	****	25.0	3.0	7.3	549.0	.9	124.0
20.0	11.6	4.0	3.5	25.0	43.0	11.1	566.0	.8	128.0
22.0	3.6	8.0	****	15.0	3.0	7.2	1010.0	2.4	102.0
23.0	4.6	9.0	****	20.0	35.0	3.0	937.0	1.9	110.0
24.0	4.7	9.0	3.8	20.0	103.0	20.9	90.4	2.6	115.0
25.0	3.5	****	****	15.0	5.0	4.3	987.0	2.1	103.1
26.0	3.4	5.0	****	20.0	3.0	16.3	970.0	20.0	102.0
27.0	3.6	7.0	****	10.0	3.0	3.6	1000.0	2.0	104.0
28.0	4.4	20.0	2.9	15.0	69.0	27.9	927.0	2.5	109.0
29.0	11.1	7.0	6.8	30.0	5.0	27.2	558.0	1.5	126.0
30.0	4.7	****	3.2	15.0	26.0	16.4	993.0	3.9	116.0
31.0	11.1	13.0	.8	25.0	3.0	4.8	547.0	1.0	122.0
32.0	3.4	13.0	5.9	10.0	81.0	19.8	976.0	2.6	105.0
33.0	6.0	20.0	****	20.0	3.0	13.5	1050.0	2.0	134.0
35.0	6.1	26.0	1.6	20.0	6.0	5.7	398.0	3.6	121.0
36.0	5.8	10.0	5.7	25.0	145.0	3.9	373.0	3.6	117.0
37.0	3.9	****	1.8	10.0	32.0	7.4	997.0	2.6	109.0
38.0	6.1	4.0	2.1	40.0	6.0	61.7	392.0	1.0	111.0
39.0	11.5	4.0	3.8	35.0	3.0	8.7	628.0	3.1	172.0
40.0	6.0	10.0	1.6	20.0	3.0	4.9	394.0	2.3	190.0
41.0	8.1	7.0	1.0	25.0	****	19.5	351.0	5.8	106.0
42.0	11.8	9.0	4.5	40.0	110.0	19.3	778.0	3.9	165.0
46.0	11.1	4.0	1.2	40.0	10.0	34.3	523.0	8.5	160.0
52.0	7.9	12.0	3.4	25.0	47.0	108.0	469.0	9.5	105.0
53.0	5.9	5.0	1.6	35.0	6.0	4.3	392.0	2.4	110.0
54.0	10.9	4.0	2.1	40.0	6.0	117.0	527.0	9.7	109.0
55.0	4.0	15.0	3.4	25.0	42.0	13.4	1290.0	4.1	187.0
56.0	3.2	10.0	5.2	70.0	45.0	283.0	358.0	9.1	101.0
67.0	12.0	4.0	7.9	20.0	3.0	60.2	518.0	1.9	162.0
68.0	11.6	3.0	5.3	****	2.0	10.9	522.0	2.8	141.0
69.0	11.6	3.0	6.1	****	2.0	19.9	509.0	2.7	143.0
70.0	11.2	3.0	4.1	10.0	2.0	22.2	513.0	2.8	140.0
71.0	4.2	10.0	2.8	10.0	3.0	21.3	878.0	6.7	121.0
72.0	7.0	4.0	8.8	10.0	2.0	16.6	409.0	3.7	120.0
73.0	6.4	3.0	9.5	25.0	3.0	11.7	497.0	2.1	142.0
74.0	8.3	6.0	3.9	40.0	2.0	15.9	453.0	9.3	162.0
75.0	4.7	8.0	3.2	25.0	3.0	62.1	457.0	5.8	109.0
76.0	6.2	11.0	4.4	10.0	3.0	809.0	501.0	11.0	117.0
77.0	6.2	7.0	4.4	25.0	41.0	100.0	517.0	9.2	119.0
78.0	9.1	6.0	6.0	35.0	3.0	25.8	467.0	3.5	151.0
80.0	7.3	1.0	3.4	15.0	****	21.4	402.0	6.9	132.0
81.0	7.4	****	6.3	20.0	4.0	10.2	430.0	1.3	116.0

Table IIIId. (Continued.)

I.D.	BE	CO	CU	PB	NI	SR	ZR	V	ZN
82.0	11.5	10.0	5.9	35.0	3.0	10.7	1240.0	3.2	224.0
84.0	10.2	14.0	5.4	35.0	3.0	16.6	1130.0	4.3	207.0
85.0	9.6	10.0	6.2	35.0	3.0	15.2	1060.0	2.4	203.0
86.0	5.0	15.0	3.7	10.0	5.0	11.6	864.0	2.4	138.0
87.0	9.4	9.0	4.5	65.0	3.0	6.1	1020.0	2.6	195.0
88.0	5.2	10.0	9.8	15.0	7.0	32.6	875.0	8.2	147.0
89.0	10.2	9.0	3.4	40.0	5.0	56.0	442.0	2.1	168.0
90.0	13.0	7.0	3.7	40.0	12.0	9.6	528.0	.5	164.0
91.0	6.4	7.0	5.0	5.0	2.0	7.6	371.0	.7	133.0
92.0	6.3	4.0	27.8	25.0	4.0	14.1	372.0	1.1	152.0
94.0	3.5	9.0	4.9	15.0	28.0	20.0	756.0	6.9	115.0
95.0	6.9	8.0	7.1	20.0	2.0	15.6	401.0	2.3	127.0
96.0	5.5	9.0	3.1	10.0	4.0	18.9	925.0	1.9	143.0
97.0	5.3	11.0	3.4	10.0	3.0	10.0	899.0	2.3	144.0
98.0	22.6	7.0	7.6	65.0	2.0	14.4	659.0	****	244.0
99.0	9.2	10.0	3.1	25.0	5.0	28.6	404.0	3.0	150.0
100.0	7.6	10.0	3.0	25.0	4.0	39.4	301.0	8.0	140.0
101.0	7.0	8.0	4.3	20.0	3.0	61.5	251.0	5.4	129.0
102.0	7.2	5.0	6.3	35.0	7.0	43.2	306.0	4.9	138.1
103.0	3.8	13.0	3.4	10.0	3.0	19.4	796.0	3.4	119.0
104.0	3.9	8.0	2.9	10.0	3.0	19.4	847.0	3.3	119.0
105.0	4.2	****	3.0	40.0	4.0	51.8	158.0	11.3	81.0
106.0	4.3	3.0	6.9	15.0	4.0	95.2	303.0	4.8	102.0
107.0	2.5	7.0	3.4	10.0	4.0	94.8	488.0	7.3	72.0
108.0	10.8	7.0	4.5	40.0	2.0	10.3	1160.0	.8	211.0
109.0	4.8	9.0	11.7	10.0	3.0	10.3	902.0	2.4	146.0
109.1	5.1	****	16.7	15.0	2.0	13.3	949.0	2.2	150.0
109.2	4.9	4.0	15.4	5.0	2.0	11.2	921.0	2.3	146.0
109.3	5.1	4.0	14.6	20.0	3.0	10.8	937.0	2.2	148.0
109.4	5.0	3.0	12.2	10.0	2.0	11.2	947.0	2.2	148.0
110.0	5.1	4.0	4.1	10.0	4.0	27.5	170.0	3.3	83.0

****=BELOW DETECTION LIMITS

Table IV. Temperature and oxygen fugacities for Black Mountain volcanic center.*

Sample No.		Temperature	f_{O_2}
Trail Ridge			
46		945 ± 46	-12.05 ± 0.51
25		816 ± 29	-15.36 ± 0.41
27		863 ± 88	-14.13 ± 1.22
30		902 ± 78	-13.73 ± 0.27
37		873 ± 20	-13.73 ± 0.27
33		949 ± 34	-12.70 ± 0.44
55	(Air fall)	888 ± 19	-10.50 ± 0.12
54	(Air fall)	853 ± 23	-11.20 ± 0.20
18		967 ± 46	-11.66 ± 0.44
103		855 ± 37	-14.18 ± 0.40
108		898 ± 40	-12.62 ± 0.41
109		876 ± 20	-13.76 ± 0.27
107		915 ± 60	-12.51 ± 0.54
Spearhead			
Civit Cat Canyon (Questionable Spearhead)			
38		749 ± 53	-16.69 ± 0.73
95		713 ± 87	-18.37 ± 1.14
73	(Air fall)	947 ± 54	12.34 ± 0.42
92	(Air fall)	778 ± 24	-15.54 ± 0.36
Nellis			
84		870 ± 98	-14.40 ± 1.09
85		970 ± 55	-13.11 ± 0.67
97		891 ± 60	-13.52 ± 0.79
39	(Air fall)	837 ± 29	-14.22 ± 0.42
East Fork Thirsty Canyon			
79		(743 ± 116)	(-17.29 ± 1.35)
94		$860 (?)$	$-14.10 \pm (?)$
77		885 ± 40	13.06 ± 0.51
74		869 ± 90	13.78 ± 1.32
76	(Air fall)	971 ± 19	-11.31 ± 0.19
Lower Thirsty Canyon, Upper Flow			
22		841 ± 29	-14.86 ± 0.40
23		829 ± 29	-15.10 ± 0.42
24		906 ± 40	-13.21 ± 0.52
67		738 ± 84	-17.06 ± 1.78
69		733 ± 58	-14.50 ± 0.85
71		859 ± 55	-14.16 ± 0.65
28		875 ± 128	-14.10 ± 0.96
Lower Thirsty Canyon, Lower Flow			
19		839 ± 62	-14.81 ± 0.90
20		834 ± 58	-14.69 ± 0.85
21		851 ± 69	-14.36 ± 1.53

* Based on ilmenite-magnetite method of Spencer and Lindsley (1981).

Table IV. (Continued.)

Sample No.	Temperature	f _{o2}
Labyrinth Canyon		
53	888 ± 37	-13.38 ± 0.42
36	855 ± 34	-13.94 ± 0.44
35	876 ± 49	-13.41 ± 0.61
Rocket Wash		
99	834 ± 81	-14.52 ± 1.14
98	771 ± 36	-15.97 ± 0.42